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# System delimitation in life cycle assessment (LCA) of aquaculture: striving for valid and comprehensive environmental assessment using rainbow trout farming as a case study

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**Abstract**
*Purpose* Life cycle assessment (LCA) has been in the last one decade used as a standardized and structured method of evaluating the environmental impacts of aquaculture arising throughout the entire life cycle. However, aquaculture system hardly applied system expansion whenever a multifunctional process has more than one functional flow. The objective of this study is to develop a methodological approach for consequential LCA and model the system expansion of the different affected processes of aquaculture.
*Methods* In this study, we have considered the system expansion in two different stages in the life cycle of the fish production: aquacultural stage, with case study of trout aquaculture, and feed manufacturing stage. Rainbow trout (*Oncorhynchus mykiss*) production was used as a case study to illustrate the method using different scenarios of system expansion.
*Results and discussion* The results of the six different scenarios of system expansion showed considerable variation among the different scenarios towards the environmental impact of trout aquaculture. Regarding global warming potential, the contributions vary by 5-fold; for acidification, variations were up to 32 %, and for land use, the contributions varied from 0.6 to 1.3 $m^2a/kg$ of trout demanded in Germany. It appeared that eutrophication is similar in all the scenarios considered.
*Conclusions* This article showed that system expansion can be used to handle the allocation issues of the co-products in the rainbow trout supply chain, thus, can be effectively used when analyzing the environmental consequences of changes in future rainbow trout production. Furthermore, consequential LCA may be important when comparing the impacts of alternative meal choices of aquafeeds. This may increase the incentive for speedy replacement of alternative meals, thus, reducing the dependence on the utilization of the limiting fisheries resources.

**Keywords** Aquaculture · Aquafeed · Consequential LCA · Life cycle assessment (LCA) · Rainbow trout (*Oncorhynchus mykiss*) · System expansion

## 1 Introduction

In the past two decades, life cycle assessment (LCA) is recognized as a standardized and structured method of evaluating the environmental impacts arising throughout the entire life cycle of a product, process, or activity (Curran 1993; Nguyen and Hermansen 2012). In aquaculture, LCA studies have been used in the last one decade focused mainly on finfish culture (Henriksson et al. 2012). The challenging issue in LCA nevertheless is the selection of methods to allocate the environmental burden of a specific production system between products and co-products. It can be regarded as crucial since using different methods would produce different results and consequently different interpretations. There are two commonly used methodological approaches in LCA: attributional LCA and consequential

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LCA. Attributional LCA is focused on description of a product system and its environmental exchanges using the average data with retrospective point of view. On the other hand, consequential LCA describes how the environmental exchanges of the system can be expected to change as a result of actions taken in the system and reflects the possible future environmental impact from a change in demand of the product under study. For example, the size of change in demand could be an increase in fish production, which needed at least 1 tonne of marginal production. Marginal data are used, which means that data from technologies affected most by this increase are included (Schmidt and Weidema 2008). The majority of LCA in aquaculture have been based on attributional LCA and only one study of mussel production (Iribarren et al. 2010) performed consequential LCA. The disctinction between attributional and consequential LCA has important consequences for the way the product system should be modeled.

The choice of whether to perform attributional LCA (mass and economic allocation) or consequential LCA (system expansion) of aquaculture is dependent on the relative difficulty of including market prospects in attributional LCA and the standards of International Standards Organization (ISO 2006). According to these standards, the first option is to avoid allocation by making use of a subdivision or to expand the systems investigated. According to Thomassen et al. (2008), it is hard to perform system expansion within attributional LCA, as no change in demand is assumed, and therefore, it is hard to assess avoided burdens in a correct way. This is mainly related to the fact that applying system expansion within attributional LCA requires an economic-causal way of thinking that is difficult to fuse within attributional LCA. It is relatively difficult to include market prospects, because the goal of attributional LCA is to assess the environmental burden of a product assuming a status-quo situation. Applying system expansion within consequential LCA agrees with the first option given in the ISO standards. The main argument for applying the consequential approach is that only the actual affected processes are included (Weidema 2003). Suppliers that are not likely to respond to a change in demand should not be included in an LCA since this will not reflect the actual change in environmental impact (Schmidt 2010).

System expansion means that the boundaries of the system investigated are expanded to include the alternative production of functions not used by the system under investigation. System expansion was applied whenever a multi-functional process has more than one functional flow. This practice narrowly reveals the effect of change in demand for co-products to identify alternate production schemes. To include the alternative way of production, a competing product with a similar function must be identified to represent indirect effects of the exported functions (Ekvall and Finnveden 2000), which are subtracted from those alternatives providing additional functions, the so-called substitution or avoided-burden method (Guinée 2002). When system expansion is performed, the environmental load of the avoided impact due substitution in most studies is subtracted (Schmidt 2010; Dalgaard et al. 2008). Similarly, in this study, system expansion is implemented using avoided or substituted impact method to identify as closely as possible the consequence of a change in demand for a co-product. What are the substitutes for co-products in aquaculture system when performing system expansion?

The objective of this study is to model the system expansion for aquaculture production. The different affected processes with co-products are selected for system expansion. Thus, in this study we have considered the system expansion of aquaculture in two different stages of production in the life cycle of the fish production: aquacultural stage with case study of rainbow trout (*Oncorhynchus mykiss*) aquaculture, and feed manufacturing stage. The aquacultural stage includes trout production and the marginal aquaculture growth. This growth ultimately is dictated by the availability of supply of aquafeed. Therefore, special focus on system expansion of aquafeed is performed assessing the different stages: fish reduction, with fish oil and fishmeal production; agriculture production; and soybean, rapeseed, palm oil, and barley production. Since the above stages of production are mostly energy intensive, system expansion at the energy stage is also considered. However, fisheries system expansion is not performed in this study due to its complexity and variability in catches and use of species for reduction that are not predictable.

In the first part (Section 2 in this paper), this article draws a methodological framework with which system expansion between species and regions can be analyzed. The second part (Section 3 in this paper) provides an illustrative example in which the methodological framework is applied to different scenarios to assess how increased demand for rainbow trout in Germany can be achieved. Section 4 discusses briefly upon the implication of the system expansion to the aquaculture production system. Finally, Section 5 presents some general conclusions.

## 2 Materials and methods

The purpose of this section is to provide a well-justified estimate of the actual production affected by a change in demand. The environmental impacts of marginal aquaculture production and the relative contributions of technology used for producing an extra tonne of aquaculture species may vary. According to Ekvall and Weidema (2004), a marginal technology is identified through five steps: (a) definition of relevant time aspects of the decision to be

supported by the LCA, (b) determining if the process affected is specific or related to the overall market, (c) identification of the market trend, (d) identification of constrained technologies, and (e) identification of the actually affected technology. The first step determines whether to include production capacity (long term) or only focus on existing production capacity (short term). If the affected process in (b) is a specific technology, then this is the marginal technology. The market trend (c) determines whether the marginal technology is to be found among the most competitive suppliers (increasing/constant trend) or the least competitive suppliers (decreasing market trend). In step (d), constrained technologies are eliminated from the list of candidates for marginal technology. Technologies can be constrained for several reasons: quotas, emission limit values, physical conditions, political constraints, or the demand for co-products. Finally, in step (e), the marginal technology is identified according to the premises given in steps (a) to (d).

## 2.1 System expansion of energy

In attributional LCA, electricity supply is commonly modeled as an average of all electricity sources within the region (Lund et al. 2010), while consequential LCA often points to either coal or natural gas (Weidema 2003; Schmidt et al. 2004). According to Lund et al. (2010), the environmental impacts of 1-kWh marginal electricity is significantly different depending on the relative contributions of technology used for producing an extra kilowatt hour. The different energy production capacities in Denmark are marginal technologies, and trends for the marginal changes in production capacity are assumed to be similar in the larger EU countries.

Lund et al. (2010) identified the environmental impacts of marginal electricity supplies on the basis of consequential LCA. Accordingly, the marginal change in electric supply most likely involves a mixture of different production technologies. Three different production capacities have been identified as long-term marginal technologies, namely coal, natural gas, and wind power. Therefore, in this study the marginal energy is considered to be natural gas-fired power plants based on the traditional consequential LCA assumptions.

## 2.2 Modeling system delimitation in farming stage

If aquaculture production is to meet its increased demand, production is increased either through increased import or increased production or a combination (Table 1). Increased production is possible through one of the following: increased area of production or increased intensity or a combination of both.

*Increased area of production* Increased area of production can be achieved using either transformation of natural/previously agricultural land for aquaculture production or appropriation of existing aquaculture farm by changing the culture species to meet the demand.

*Increased intensity* Increased intensity on the other hand indicate an increase in stocking density per unit area of production, resulting in increased production; or manipulation of the genetic make-up of the culture species in order to achieve a fast-growing fish and therefore increasing production per unit area and per unit time. However, genetic manipulation/modification in fish is not permitted in Germany. Although it is difficult to account the impact of the genetic modification at present, placing such impact in one impact category is very important in the future. Thus, the increased intensity using genetic manipulation will not be considered in this study.

It is well known that increased import replaces marginal demand and the marginal supplier must be able to produce in another region. Such production mainly involves increased use of production area or increased intensity of production. Consequently, the abovementioned points (i.e., increased production by area or increased production by intensity) also apply in a different geographical region but at the same impact category.

Replacement of other aquaculture species to another to meet the demands suggest that the species replaced must either be marginally supplied through import or is completely forgone. Thus, the marginal production will be displaced by the new species in demand. If it is assumed that the increased production of the new species does not affect the overall global fish production, the displaced species will be compensated for in the region representing the marginal supplier of that species (i.e., production in another place therefore increased production of the species and thereby increased area of production or increased intensity).

Accordingly, changes in aquacultural production of a certain species can principally be achieved by affecting one or a combination of the four different systems:

1. Changes in productivity per unit of area (e.g. fertilizer, stocking density, feeding, and medication).
2. Transformation of land between previously agricultural land or natural noncultivated land and aquaculture.
3. Change in species of culture affecting the area of displaced species.
4. Change in productivity per unit time (e.g., GMO). However, in this study this particular modeling system will not be considered, mainly due to the strict regulation of the use of genetic manipulation in aquaculture in the EU and we attempt to maintain the systems that are close to existing real situation.

System 1 Change by yield

When aquacultural production is increased by change in yield, there are no effects on land use. Only the

**Table 1** Different scenario for marginal production of trout in Germany using consequential LCA

| | Increase demand for 1 kg of trout in DE | Scenario I | Scenario II | Scenario III | Scenario IV | Scenario V | Scenario VI |
|---|---|---|---|---|---|---|---|
| 1 | Is trout produced in DE? | Yes | Yes | Yes | Yes | No | No |
| 2 | Does increased production of trout affect the culture of other products? | No | No | Yes | Yes | – | – |
| 3 | How does increased production of trout met in DE? | | | – | | – | – |
| | Change in area (%) | 100 % | | | | | |
| | Change in yield (%) | | 100 % | | | | |
| 4 | What is the marginal fish in DE? | – | – | Carp—1 kg | – | – | |
| | 1 kg*( yield of marginal fish/yield of trout) | | | Production of carp and trout per cubic meter is assumed to be equal | | | |
| | NB—the marginal fish is displaced by trout in DE | | | | | | |
| 5 | Which region is the marginal supplier of the marginal fish? | – | – | China—carp production | – | – | |
| | 1 kg*(yield of marginal fish/yield of trout) | | | | | | |
| | NB—increased demand for the marginal fish | | | | | | |
| 6 | Are changes in the marginal fish compensated for? | – | – | Yes | | – | – |
| 7 | How is the increased production of the marginal fish met in region where the marginal fish originated? | – | – | | | – | – |
| | Change in area (%) | | | 100 % | | | |
| | Change in yield (%) | | | | 100 % | | |
| 8 | Which region is the marginal supplier of trout? | – | – | – | – | DK | DK |
| | Increased demand for trout in the marginal supplier | | | | | | |
| 9 | Are changes in trout compensated for in the marginal supplier region? | – | – | – | – | Yes | Yes |
| 10 | How is increased production in the marginal supplier region for trout met? | – | – | – | – | | |
| | Change in area (%) | | | | | 100 % | |
| | Change in yield (%) | | | | | | 100 % |

*DE* Germany, *DK* Denmark

interventions per unit area are affected. However, increased intensity to increased yield suggests that there is change in water use, feeding provision, and use of fertilizer. The principle is illustrated in Fig. 1.

System 2 Change by area

When aquaculture production is increased by a change in the cultivated area, there are two different processes of transformation, each with its own significance:

(a) Change from an agricultural land to aquaculture: this includes occupation processes of agricultural land and the emission from aquaculture operation itself (Fig. 2a). Here, the implications related to the transformation process itself, i.e., transformation process of land and the associated changes in the standing stocks of carbon and nitrogen is accounted.

(b) Change from the natural noncultivated land to aquaculture. This includes occupation processes of natural noncultivated land to aquaculture and the emission from the aquaculture production itself (see Fig. 2b). Here, the implication related to the transformation processes itself, i.e., transformation process of the land, and the associated changes in the standing stocks of carbon and nitrogen is accounted.

It is well known that even pristine nature causes undesirable emissions, thus, the impacts from cultured fish should be represented by the difference between the actual impacts from aquaculture and the impacts

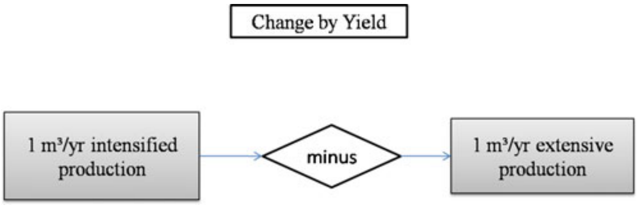


**Fig. 1** Principle in modeling of changes in aquacultural production by a change in yield. The output from this system is equal to the difference in yield of the two processes. Increased yield implies increased use of resources and corresponding outputs, which need to be assessed

from the alternative land use, i.e., commonly land under natural vegetation.

Figure 2b demonstrates a simplified form of the relation between impacts (impacts from aquaculture production and the avoided interventions from natural noncultivated land), because the impacts from transformation of 1 ha of noncultivated natural land into 1 ha of aquacultural land is difficult to relate to the functional unit, because it is difficult to predict how many functional unit the land transformation will support. Therefore, the implication related to the transformation process itself is treated separately in life cycle impact and life cycle impact assessment (LCIA) based on the recent database for land transformation (Schmidt 2008).

System 3 Displacement of other species

When aquaculture production of species X is changed at the expense of culturing another species Y, the displaced species Y must be produced somewhere else, i.e., in region that represents the marginal supplier of species Y. The amount of displaced species Y per hectare production of species X is determined as ($Q_Y/Q_X$), where $Q$ is yield per hectare per year. The change in production of species Y then have to be distributed on change by area and changes by yield. The principle is illustrated in Fig. 3.

## 3 Application of the LCA methodology—rainbow trout aquaculture case study

To facilitate the application of the above method and to monitor the effect of different scenarios for how increased demand in aquaculture products can be attained, this section presents a case study illustrating the increase in demand of rainbow trout aquaculture in Germany. LCA is used to evaluate the environmental impact of rainbow trout.

### 3.1 Definition of goal and scope

The goal of this case study is to compare different methods of handling co-product allocation using several scenarios of system expansion when dividing the environmental burden of rainbow trout production. The scenarios studied are listed in Table 1. In this article, the results for the impact categories

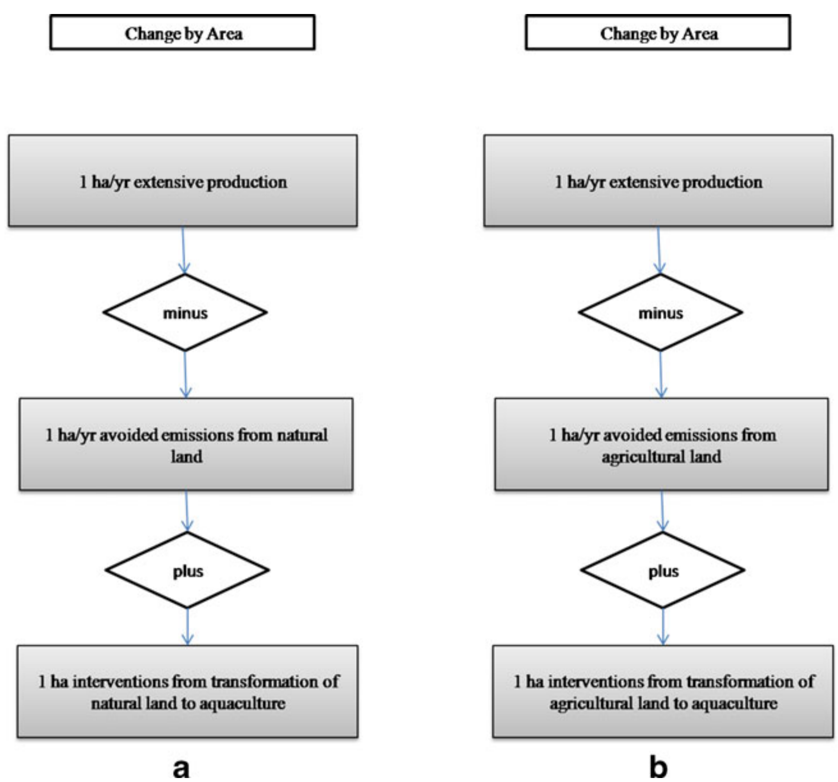


**Fig. 2** Principle in modeling of changes in aquacultural production by area. The output from this system is equal to annual yield of the relevant culture species considered

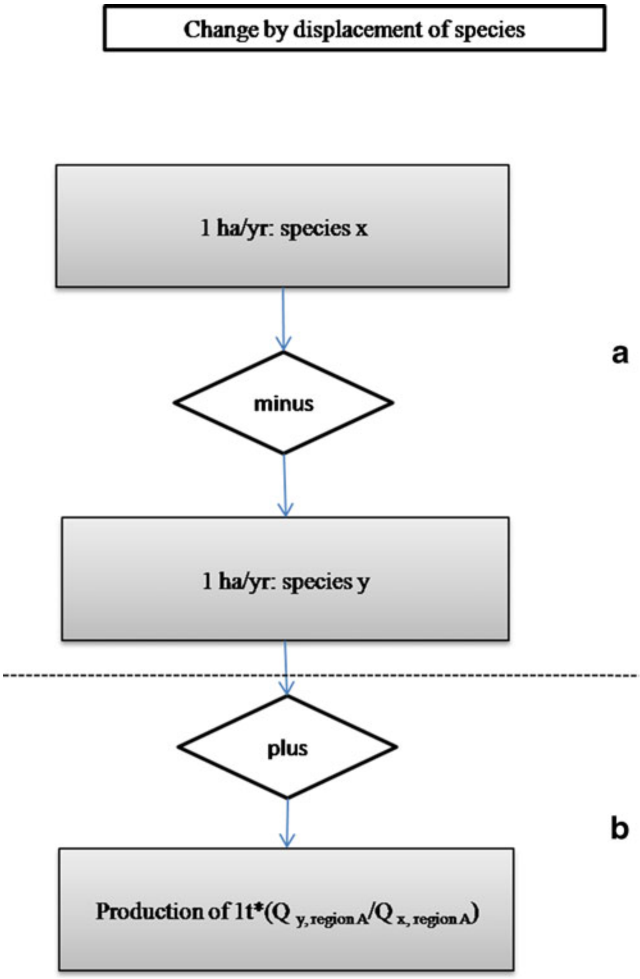


**Fig. 3** Principle in modeling of changes in aquacultural production by displacement of culture species. *A* Region A. *B* Region B

acidification, eutrophication, global warming, and land use are presented for the various scenarios of handling system expansion.

### *3.1.1 Scope of the study*

Two systems have been studied in detail. The farming system is the foreground system, and the main product of which is rainbow trout. The background system, requiring further system expansion is the feed manufacturing system. The co-products from the different systems, i.e., meeting the increased demand for rainbow trout through systems expansion, can be considered as products entering the background system where they displace production providing the same function. The avoided burdens are the displaced burdens in the extended system.

### *3.1.2 System description and boundaries*

The production of rainbow trout begins from extraction of raw materials and ending with the harvest of live fish at the farm gate (see Fig. 1). The raw materials vary from resources extracted for the supply of energy to mineral resources used for manufacturing chemical fertilizers, including fish resources used as feed ingredients. The production system of rainbow trout includes feed raw-material production, feed manufacturing, hatchery, grow-out fish cultivation, transportation of materials, fuels, and electricity used in all the process of the aquaculture system. The main raw materials of feed are fish meal and oil and crop-derived raw materials. Not all units of production are included due to either lack of reliable data. Consequently, antibiotic and chemical use and infrastructure are not included.

The study includes production of all inputs and outputs of rainbow trout production system. The boundary is the farm gate. Infrastructure is excluded from the analysis. Allocation is avoided by expanding the rainbow trout system to include the alternative ways of producing co-products used in the system. The alternative ways of producing trout is assessed within each of the scenarios are described in Section 3.2 and are compared in Table 1.

### *3.1.3 Functional unit*

The functional unit (FU) of the rainbow trout production system is 1 tonne of live, whole fish leaving the farm gate.

## 3.2 System expansion in farming stage: scenario modeling

The scenarios are defined correspondingly to the model system in Section 2.2 above. Scenarios I and II represent the two conventional ways in which system 1 can be affected, i.e., rainbow trout production is increased in Germany either by increased area for production or increased yield through intensity. Scenarios III and IV represent a situation in which system 2 is affected, i.e., rainbow trout production in Germany displaces carp production, which in turn is compensated for by increased production in China either by increased area or increased intensity. Scenarios V and VI represent the two alternative ways similar to scenarios I and II, but in which increased demand of rainbow trout is met by increased import produced either by increased area or increased yield in Denmark.

It is important to note that not all scenarios are realist in meeting how increased demand of rainbow trout is achieved. However, this article does not aim at suggesting which scenarios are most likely to augment the marginal supply of rainbow trout, rather assess the potential environmental impacts of aquaculture using different scenarios of system delimitation.

Some aspects of system delimitation for fish farming mentioned above have not been formally addressed. In this study, we have approached some of these aspects using the following assumptions.

#### *3.2.1 The identification of marginal/actually affected culture species and regions due to increased demand for trout*

It is relevant to clarify if increased trout production in Germany is by increasing yield or by increased area, i.e., transformation of nonaquaculture area to one. This may include displacement of intermediate culture species due to the strict environmental and water regulation in Germany; for example, increased trout production in Germany displaces carp production; this displaced carp production may be produced in China either by intensification or by expanding aquacultural land. The difference in environmental impact between the two strategies are significant, especially increased culture area has land use and water use effects, while increased yield may have more pronounced effects relating to global warming and eutrophication. China is the largest producer of carp (FAO 2010). In this scenario modeling, it is assumed that China's supply of carp to EU can allow the avoided production of carp in EU due to the marginal production of trout.

#### *3.2.2 The identification of marginal/actually affected feed ingredients to meet increased demand for trout*

Increased demand for trout implies that increased in feed production is inherent. However, feed for trout at the moment is based on fishmeal and fish oil, as protein and energy sources, respectively. Fishmeal and fish oil have increasingly been used in both aquaculture and livestock production as feed ingredients, mainly due to the unique characteristics of these two resources and their availability as cheap protein sources. Recent price hike has forced the livestock industry to decrease the use of fishmeal and fish oil as feed ingredients. In response, rapid growth of aquaculture production coupled with improved feed conversion ratio in the last decade has more than doubled the share of aquaculture's consumption of fishmeal and fish oil to 68 and 88 %, respectively (Naylor et al. 2009). However, facing the predicted aquaculture growth in the next few years and the stagnating fishmeal and fish oil production, it is necessary to find alternative sources of protein. Therefore, increase in trout production, which consequently effect in increase in demand for fishmeal and fish oil, need to find alternative protein and energy source. Several studies have demonstrated that fishmeal can be completely replaced using rapeseed meal (Slawski et al. 2011) or soybean meal (Yang et al. 2011), and partial replacement with other unconventional protein sources such as potato protein concentrate (Tusche et al. 2011), is possible. Furthermore, increased feed production may be met sufficiently by either yield increase or area expansion for rapeseed (Schmidt 2010) and soybean (Dalgaard et al. 2008). System expansion in feed manufacturing is described in detail in Section 3.3 below.

#### *3.2.3 Avoided environmental impacts from nonaquaculture land into one*

It is well known that even the pristine nature causes undesirable emissions, though the levels are commonly insignificant than that of the aquaculture production sites. Thus, intervention from cultivation of trout and carp should be represented by the difference between the actual interventions from aquaculture and the interventions from alternative land use, i.e., commonly land under natural vegetation.

### 3.3 System expansion in feed manufacturing

Here, we investigated the system delimitation of feed manufacturing with using an example for trout aquaculture in Denmark. The fish reduction system is expanded because fish meal and fish oil are co-products. When identifying the avoided burden of fish oil, the question to be asked was: what will be used when the supply of fish oil is stable or less of fish oil is produced?

#### *3.3.1 System expansion at feed manufacturing stage*

Overall, the potential to substitute plant-based proteins into aquafeeds is high but will depend on their relative process, availability, and palatability for individual species. Although several studies have demonstrated a complete replacement of fishmeal with plant proteins is relatively simple, progress is expected to be slower in reaching the goal of fishmeal replacement with plant protein at an industrial level. Thus, in this study, we have taken a conservative replacement of half of the fishmeal with soybean meal concentrate in the diets of rainbow trout.

The past decade had seen an increase in the use of terrestrial plant oils, such as rapeseed, soy and palm oils, to replace fish oil in aquafeeds. This replacement has been driven by the increasing cost of fish oil. Beyond the price advantage, terrestrial plant oils can be produced in sufficient quantities to meet growing demand of aquaculture. The major sources of replacement for fish oil in rainbow trout diets include sunflower, linseed, rapeseed, soybean, olive, and palm oils (Naylor et al. 2009).

However, replacement of fish oil with terrestrial plant oils in the aquaculture result on lower concentrations of the beneficial long chain omega-3 fatty acids, which are mainly composed of eicosapentaenoic acid (20:5$n$–3) and docosahexaenoic acid (22:6$n$–3) (Mourente and Bell 2006). Plant oils do not contain long chain omega-3 fatty acids. As a result, terrestrial plant oils and fish oil blends are used in manufacturing aquafeeds in the growout phase of the farming stage and later switching to complete fish oil-based diet to increase long chain omega-3 oil levels in fillets.

After careful assessment, there was little if any material available in large quantities to meet the demand of products

high in long-chain omega-3 fish oil content, which is favored by consumers for health reasons. In other words, the rising demand for species high in fish oil could lead to continued increases in the amount of forage fish used in feeds (Naylor et al. 2009). Furthermore, volatile commodity markets have been disrupting the smooth transition in feed ingredient substitution at the industry level. Unless appropriate substitutes to feed ingredients are found, growth in the aquaculture sector is like to push prices for the relatively limited quantities of fish oil. Trout are the most efficient converters of macronutrients to biomass, but they rely on energy-dense nutrients (lipids) and feeds made with high-quality ingredients (Naylor et al. 2009). Even though a share of plant-based lipids incorporated in trout diets has been increasing, fish oil remains a key ingredient.

In this study, we assumed that the present use of fish oil will continue in the future, despite limitation in supply and increasing price. Accordingly, a new model is important to be investigated for marginal supply of fish oil to fulfill the increasing trout aquaculture development. This assumption further serves to simplify the model in identifying marginally affected products when expanding the feed system.

The potential to expand the use of terrestrial plant-based lipids in the short to medium term is promising. For example, several studies have demonstrated that fish oil can be completely replaced with terrestrial plant oil in fish without compromising growth, performance, or fish health as long as the long-term omega-3 fatty acid requirements are met (Naylor et al. 2009). Such substitution has the potential to alleviate the pressure on forage fisheries from aquaculture in the long term. In the short and medium terms (5–10 years), where this study aimed to estimate the marginal production, the use of fish oil will remain a key ingredient in supplying long chain omega-3 fatty acid in fish diets.

Increase in trout production mean increase in fish oil consumption. The marginal increase in trout production must therefore use the available fish oil production since fish oil production remains constant. Therefore, the adjustment in use of fish oil in some aquaculture species must be forsaken. The largest production in aquaculture is in the cultivation of carp (60 % of total aquaculture production; FAO 2010). Carp uses a considerable portion of fish oil in feed (6 % of total fish oil used in aquaculture, IFFO 2008). Carp production can be sustained using fish oil contained in fishmeal. The avoided fish oil can therefore be used by trout production. Thus, the ultimate affected production is the most flexible production: carp aquaculture. Therefore, fish oil required for trout production must come from other marginal aquaculture species, which at present is using fish oil. Carp is recognized as a marginal product in this assessment, and fish oil destined for use in carp production can be used for marginal trout production. Figure 4 illustrates the system expansion of aquafeed manufacturing. Therefore, the marginal supply of fish oil for trout feed must therefore come at the expense of its use in marginal fish production. Clearly, reducing the use of fish oil from use in carp aquaculture can supply sufficient quantities of fish oil to carnivorous fish such as trout. Carp which consumes large portion of fish oil need to find alternative source because it can afford to do so (carp being herbivorous fish in natural environment; Kaushik 1995).

#### *3.3.2 System expansion at agricultural stage*

The feed manufacturing also depends on agricultural products that need to be dealt with system expansion. Furthermore, energy uses in the manufacture of feed need a similar expansion to identify the marginal energy source. The agricultural and energy system expansion have been dealt with in previously published studies (Schmidt 2007, 2010; Dalgaard et al. 2008); the results of which has been used in this LCA.

### 3.4 Life cycle inventory analysis

Inventory analysis was carried out according to ISO 14044 (ISO 2006). SimaPro 7.2 software (Pré 2010) was used to calculate the inventory results.

#### *3.4.1 Fisheries and fish reduction*

Fishmeal and fish oil are important source ingredients of trout feed produced during fish reduction process. The different species of fish used for reduction are captured from the marine environment (details of the different species considered are mentioned in the Electronic supplementary material). The harvested fish are then brought to the fish reduction plant for fish oil extraction. Fish oil is separated from its by-product fishmeal (details are presented in the Electronic supplementary material).

#### *3.4.2 Soybean, palm oil, and barley production*

This process encompasses the entire production process associated with soybean, palm oil, and barley. It includes the entire life cycle of the plant: planting, fertilizing, treatment with different pesticides, and plant collection. Also, we have taken into account the processes of operating with farm machines including energy to use and the different impacts derived of its use (Schmidt 2010; Dalgaard et al. 2008). Drying and preparation of seeds for meal and oil extraction is also included in the inventory, where the prepared (crashed and pressed) oil seeds pass through a milling process to obtain meal and oil.

#### *3.4.3 Feed manufacturing*

During the manufacturing of feed proximate composition of ingredients (Tusche et al. 2011) and the consumption of

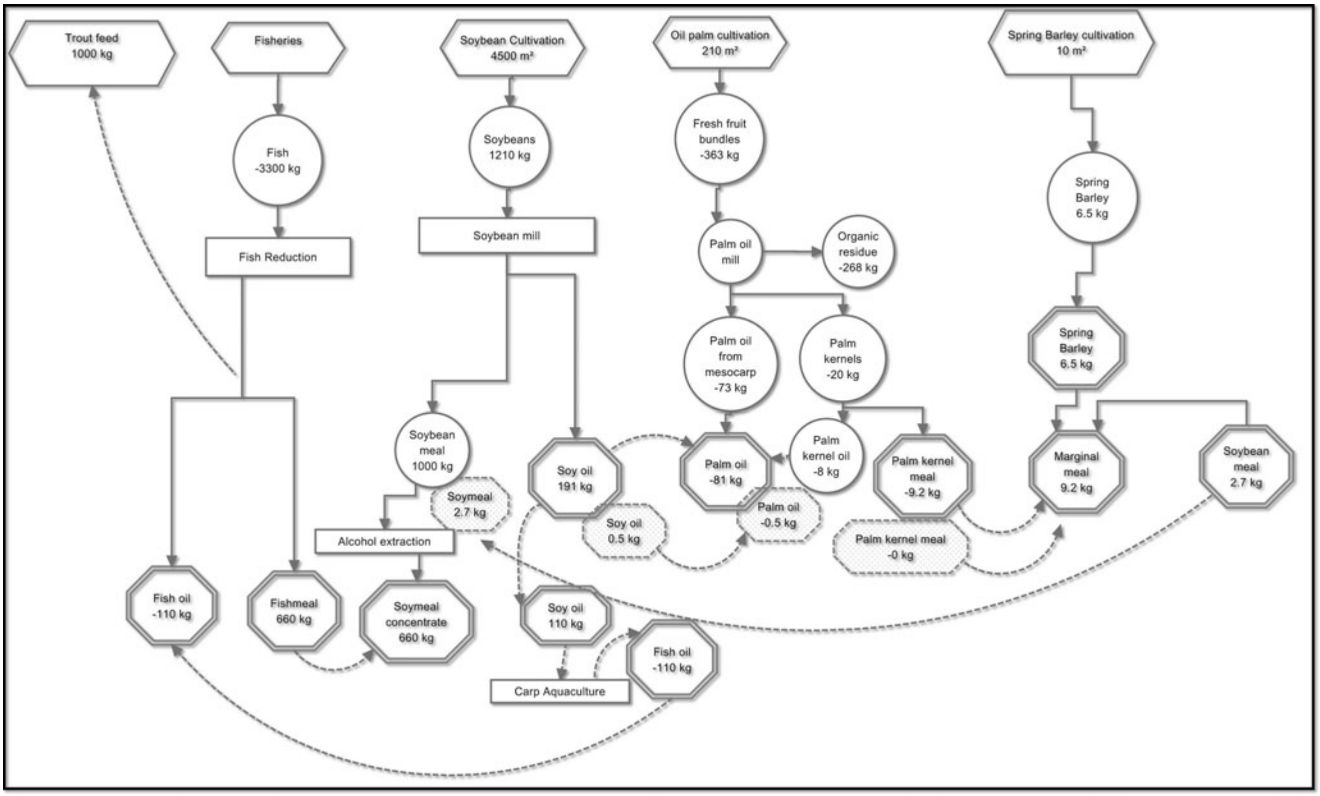


**Fig. 4** System expansion of aquaculture product system related to the manufacture of 1 tonne of aquafeed for rainbow trout

energy during the manufacturing of extruded pellets is accounted in this study (Table 2). This process includes the energy used for milling, mixing, extruding, drying, and cooling. The inventory data of feed manufacturing were collected form a feed factory in Denmark. Details of conventional aquafeed production process are presented in the Electronic supplementary material.

### 3.4.4 Rainbow trout farming

This process encompasses the entire production processes associated with trout aquaculture in the different production systems. It includes water use, feed use, land use, and treatment with different compounds for sanitation. Furthermore, fuel used for transportation of feed and materials, as well as energy used in running the different motors and machinery during production are accounted for accordingly. The life cycle inventory of rainbow trout production in Germany is based on the data collected from different trout farms in Germany (Table 3). The background inventory was based on literature and Ecoinvent database contained in Sima Pro 7.2 software. The different scenarios considered are modeled according to the assumptions mentioned in the previous section; and the material and energy flow for each is summarized in Table 3.

## 3.5 LCIA—comparison of scenarios

The life cycle environmental impacts associated with trout production were quantified using the problem-oriented approach, CML 2 (Center for Environmental Studies, University of Leiden) baseline (2000) method. The impact categories included in this analysis were: acidification potential, global warming potential, land competition, and eutrophication potential. Furthermore, comparative analyses among the different rainbow trout production scenarios were performed using the chosen impact categories. The choice of the impact categories is dependent on the environmental impacts of aquaculture. Lack of data for some background processes and unavailability of characterization factors for impacts that are specific to aquaculture has limited this study to consider only four impact categories, but is still acceptable by ISO 14044 standards. Comparison of the LCIA for the six scenarios considered is shown in Fig. 4.

## 3.6 Interpretation

The results of the impact assessment are interpreted based on the need for comparison of the different production systems and identification of "hot spots" and environmentally impacting processes for future improvements; and conclusion and recommendation are drawn from them.

**Table 2** Material flow of standard rainbow trout feed (after Tusche et al. 2011) manufacturing showing material inputs and outputs as well as use of energy

| Ingredients | Unit | Standard<br>Standard feed |
|---|---|---|
| Inputs | | |
| Materials | | |
| Fishmeal[a] | kg | 660 |
| Fish oil[a] | kg | 110 |
| Wheat starch[b] | Kg | 170 |
| Mineral mixtures[d] | kg | 20 |
| Vitamin[c] | kg | 10 |
| Energy | | |
| Diesel | kg | 0.198 |
| LPG[§] | kg | 1.17 |
| Electricity | kWh | 0.011 |
| Heat | kWh | 148 |
| Outputs | | |
| Trout feed | kg | 1,000 |

[§] *LPG* liquefied petroleum gas

[a] VFCUX, Cuxhaven, Germany

[b] Cargill Deutschland GmbH; Krefeld, Germany

[c] Vitamin premix (in milligrams per kilogram); Vitfoss, Grasten, Denmark: vitamin A, 1,000,000 IU$kg^{-1}$; vitamin D3, 200,000 IU $kg^{-1}$; vitamin E (as α-tocoferol-acetate), 40,000; vitamin K3 (as menadione), 4,000; vitamin B1, 4,000; vitamin B2, 8,000; vitamin B6, 4,000; vitamin B12, 8; vitamin C (as monophosphate), 60,000; pantothenic acid, 8,000; nicotinic acid, 40,000; folic acid, 1,600; biotin, 100; and inositol, 40,000

[d] Mineral premix (in milligrams per kilogram); Vitfoss, Grasten, Denmark: cobalt (as cobalt sulfate), 400; manganese (as manganese sulfate), 2,500; iodine (as calcium iodine), 500; copper (as copper sulfate), 2,500; selenium, 25; and zinc (as zinc sulfate), 28,000

### 3.7 Results

It appears from Fig. 5 that the contributions to the included impact categories resulted in considerable variation among the different scenarios. Regarding global warming, the contributions vary by 5-fold; for acidification, variations are up to 32 %, and for land use, the contributions varies from 0.6 to 1.3 $m^2a$/kg of trout demanded in Germany (Table 4). It appears that eutrophication is similar in all the scenarios considered. Scenario IV showed the highest impact in all the categories, except land use. This is mainly related to the fact that species replacement throughout the life cycle of the rainbow trout production is associated with high energy utilization in agriculture and aquaculture practices and the associated intensity associated to increasing the yield. Similarly, land use is the highest for scenario III because of the extensive area required to grow marginal rainbow trout through area expansion, and the production of alternative plant proteins used to displace fishmeal during system expansion. In general, this means that intensification causes increased global warming and acidification potential related to energy use, as well as processing of alternative plant-based proteins sources.

## 4 Discussion

From the material flow results of trout farming using the several scenarios, it is demonstrated that various system expansion methods had various LCIA results. In general observation, the results of the LCIA showed that scenario IV has the highest impact in three of the four impact categories chosen. While scenario III showed higher land use. Seen overall, environmental impact of aquaculture is higher in scenarios III and IV. Considering the aim of the LCA, if the desire of LCA is to be used adequately for decision making, scenarios III and IV may cover most part of the actual potential impacts. These describe best the actual affected processes, the identification of marginal suppliers, and the prediction of how product increases (area or yield) are often attended when making decisions. In any case, it should be ensured that undesirable decisions based on wrong assumptions about unforeseen impacts are avoided by selecting the scenario with the highest impact in our LCA. However, it is important to keep in mind that, it is hardly possible to actually predict which scenarios result closest to the real environmental impacts.

The preference of fish meal as protein source is not disputable due to its high digestibility of dry matter, energy, and the availability of amino acids. Digestibility of several plant protein meals such as rapeseed meal and soybean meal is similar to fish meal in trout (Slawski et al. 2011; Drew et al. 2007; Yang et al. 2011; Mambrini et al. 1999). The disadvantage of these well-digested, high-protein ingredients, compared with fish meal, was that the essential amino acid contents, profile, and availability of these ingredients were inferior to fish meals (Allan et al. 2000). Furthermore, antinutritional components play an important role in the readily substitution of fishmeal by plant protein meals. However, the growth of aquaculture can only be assured through the supplement of available fishmeal, with stagnant growth prospective, using these plant meals. System expansion is important to help assess the environmental impacts of these alternative meals, consequently, making informed decision to select the different meal choices. Apart from the limiting supply of fishmeal, comparing the alternative meal choices can also be an incentive in speedy substitution of fishmeal by the industry, before subsequent price increases facilitate environmental disaster through collapse of the supply from fisheries.

**Table 3** LCI of rearing 1 tonne of rainbow trout using different scenarios of system expansion at the farming stage

| Scenarios | | Scenario I | Scenario II | Scenario III | Scenario IV | Scenario V | Scenario VI |
|---|---|---|---|---|---|---|---|
| Description | Unit | Area expansion in DE | Increase intensity in DE | Area expansion in CN | Increased intensity in CN | Area expansion in DK | Increased intensity in DK |
| Inputs | | | | | | | |
| Materials | | | | | | | |
| Land use | $m^2a$ | 1,600 | 20 | 1,600 | 20 | 1,600 | 20 |
| Water use | $m^3$ | 473,040 | 4,380 | 473,040 | 4,380 | 473,040 | 4,380 |
| Feed | kg | 1,200 | 913 | 1,200 | 913 | 1,200 | 913 |
| Energy | | | | | | | |
| Transport | tkm | 540 | 385 | 840 | 685 | 1,040 | 885 |
| Transport | tkm | – | – | 8,000 | 8,000 | – | – |
| Electricity | kWh | – | 2,554 | – | 2,743 | – | 2,554 |
| Outputs | | | | | | | |
| Rainbow trout | kg | 1,000 | 1,000 | 1,000 | 1,000 | 1,000 | 1,000 |
| Emission to water | | | | | | | |
| Phosphorus | kg | 4 | 4 | 4 | 4 | 4 | 4 |
| Nitrogen | kg | 57.8 | 57.8 | 57.8 | 57.8 | 57.8 | 57.8 |
| Emission to soil | | | | | | | |
| Phosphorus | kg | 6 | 6 | 6 | 6 | 6 | 6 |
| Nitrogen | kg | 7.2 | 7.2 | 7.2 | 7.2 | 7.2 | 7.2 |

The use of fishmeal as a source of energy in carp is well documented (Kaushik 1995) and similar results have also been reported for silver perch (Allan et al. 2000) showing efficient lipid digestibility, thus energy from lipids in the fishmeal. This has been the basis for the marginal supply of fish oil made available to trout feed from the large quantities used in carp feed at present.

Plant-based protein can partially or totally replace animal protein sources in the diets of most culture fishes. For example, Slawski et al. (2011) and Drew et al. (2007) partially substituted fishmeal by rapeseed protein concentrate in the diets of rainbow trout. Similarly, Yang et al. (2011) have substituted up to 60 % of fishmeal with soybean meal without significant effect in growth performance of rainbow trout. Trout appear to efficiently utilize dietary soybean meal when partially substituted and supplemented with essential amino acid profile of the diet. However, there are several soybean products with potential to replace fishmeal. The different soybean products are soybean meal, full-fat soybeans, soy isolates, and soybean concentrates. Each of these products has different substitutability and different results in growth. This is attributable mostly to processing technologies involved and to the presence of various antinutritional factors (Slawski et al. 2011;

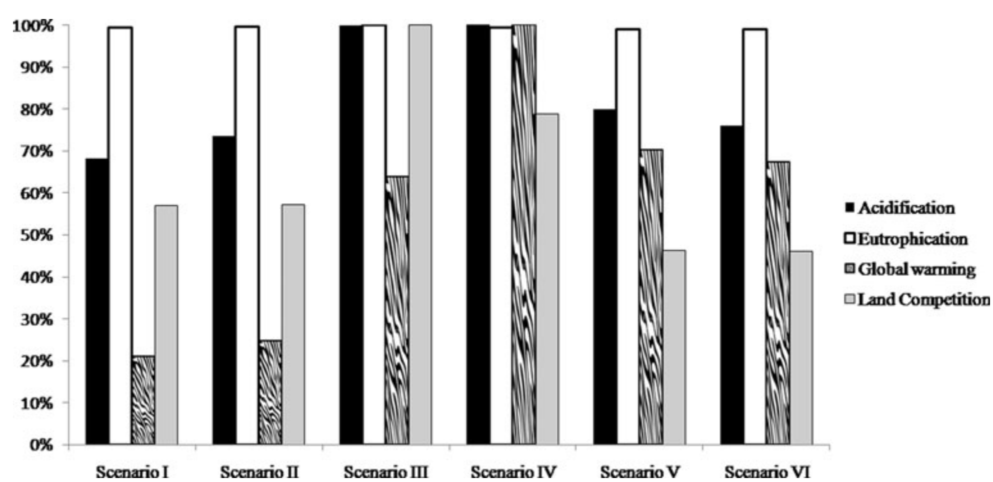


**Fig. 5** Relative emission load of rainbow trout aquaculture using different system expansion scenarios. Each scenario is compared across the selected impact categories

**Table 4** Relative emission load of rainbow trout farming estimated following different scenarios of system expansion

| Impact category | Unit | Scenario I | Scenario II | Scenario III | Scenario IV | Scenario V | Scenario VI |
|---|---|---|---|---|---|---|---|
| Acidification | kg $SO_2$ equivalent | 7.7 | 8.3 | 11.3 | 11.3 | 9.0 | 8.6 |
| Eutrophication | kg $PO_4$ equivalent | 60.0 | 60.1 | 60.4 | 60.1 | 59.9 | 59.8 |
| Global warming | kg $CO_2$ equivalent | 767 | 900 | 2,322 | 3,633 | 2,552 | 2,450 |
| Land Competition | $m^2a$ | 742.2 | 744.0 | 1,303.0 | 1,026.8 | 601.3 | 599.6 |

The results are characterized results and are related to the FU: 1 tonne of rainbow trout demanded in Germany

Escaffre et al. 1997). Therefore, care must be taken when choosing a soybean meal for analysis to identify which product can potentially substitute fishmeal in trout feed and digestibility maintained.

## 5 Conclusions and perspectives

The six scenarios chosen for system expansion conform to common aquaculture growth practices of increasing yield, where extensive production systems are more environmentally efficient than intensive production systems, and intensification of production causes increase in emissions but has no effect on land use, while expansion through extensive production causes less emissions but required more land. It is evident from this study, that in order to obtain a comprehensive picture of the environmental effects of rainbow trout production the system must be studies in an integrated manner involving systems affected by the marginal increase in production. System expansion to handle the allocation issues of the co-products in the rainbow trout supply chain effectively addresses in integrating these affected systems, thus, can be used when analyzing the environmental consequences of changes in future rainbow trout production. Furthermore, consequential LCA may be important when comparing the impacts of alternative meal choices of aquafeeds. This may increase the incentive for speedy replacement of alternative meals, thus, reducing the dependence on the utilization of the limiting fisheries resources. In general, this methodological approach and case study proved that the implementation of consequential LCA in evaluating environmental impacts of aquaculture can be useful for making a gross evaluation and comparison of the aquaculture product system.

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